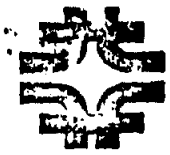

Fermilab

RADIATION PHYSICS NOTE #14

October 15, 1976

To: Chuck Brown

From: Peter Gollon L. Coulson

Subject: Doses From Hadron Beams

I have looked at the question that you and B. J. Holt raised concerning conversion from hadron flux to dose (rads) and dose-equivalent (rems) for high energy hadron beams. I will present an analysis which should be comprehensible to experimenters whose knowledge of radiation protection doesn't seem to extend past the blue-book tables.

1. Minimum-ionizing muons lose energy in carbon at about 1.7 MeV/gm cm^{-2}; or 2.7×10^{-8} rad/muon cm^{-2}. Inverting this gives the canonical 3.7×10^{7} muons/cm^2 rad.

2. High energy protons lose energy by ionization at an identical rate. They also deposit energy as a result of strong interactions with nuclei, such energy is deposited via nuclear fragments, secondary p, $\pi^{\pm}$, γ from π°, etc. We have measured[2] the total energy deposition in a shorter ($\lambda/5$), narrower (1" dia.) Be target to be twice that resulting from the primary ionization alone. Armstrong and Chandler[1] calculate a total energy deposition for a broad-beam irradiation of a 30 cm slab of tissue of about 5 times the primary ionization. I believe these results are consistent, given the differences in geometry, target length and materials.

   I therefore have a reasonable degree of confidence in the following maximum dose conversion factors for a broad-beam irradiation, which they calculate:

Proton Energy	rad/proton cm^{-2}
20 GeV	1.5×10^{-7}
200 GeV	2.2×10^{-7}

(The term "maximum" refers to the maximum within the person's body, which occurs on the downstream side; values averaged along the beam are about 20% lower. The maximum values are more appropriate to a one or two pulse irradiation.)

3. So far we have only talked about energy deposition, or rads. The legal unit of radiation exposure, the rem, was designed to be a better measure of biological effects of radiation. To construct rems from rads, the energy deposited by each particle is weighted by a "quality factor" which depends on the rate of energy deposition (dE/dx) of that particle. Quality factors range from 1 for $e^{\pm}$ and $\mu^{\pm}$, to 20 for highly ionizing nuclear fragments. According to ref. 2, about 20% of the energy deposition from 200 GeV protons results from multiply charged nuclear fragments. (This is ~ 150 MeV per interaction via nuclear fragments.) If we take a quality factor of 20 for these fragments and 1 for everything else, the mean quality factor is:

$$\bar{Q} = 20 \times 0.2 + 1 \times 0.8 = 4.8$$

Reference 2 actually calculates $\bar{Q} = 3$ at 20 GeV and $Q = 5$ at 200 GeV. Multiplying the rad conversion factors given above by these quality factors gives:

Proton Energy	rem/proton cm^{-2}	Protons/cm^2 for 1 rem
20 GeV	4.8×10^{-7}	2.1×10^{6}
200 GeV	12×10^{-7}	0.8×10^{6}

The numbers in the last column are the ones which you were questioning.

REFERENCES

1. T. W. Armstrong and K. C. Chandler, ORNL-TM-3758 (1972)

2. M. Awschalom, et al., Nucl. Inst. & Meth. 131, 235 (1975)

PG/jo
Encl.
cc: B. J. Holt
S. Eckland
T. E. Toohig

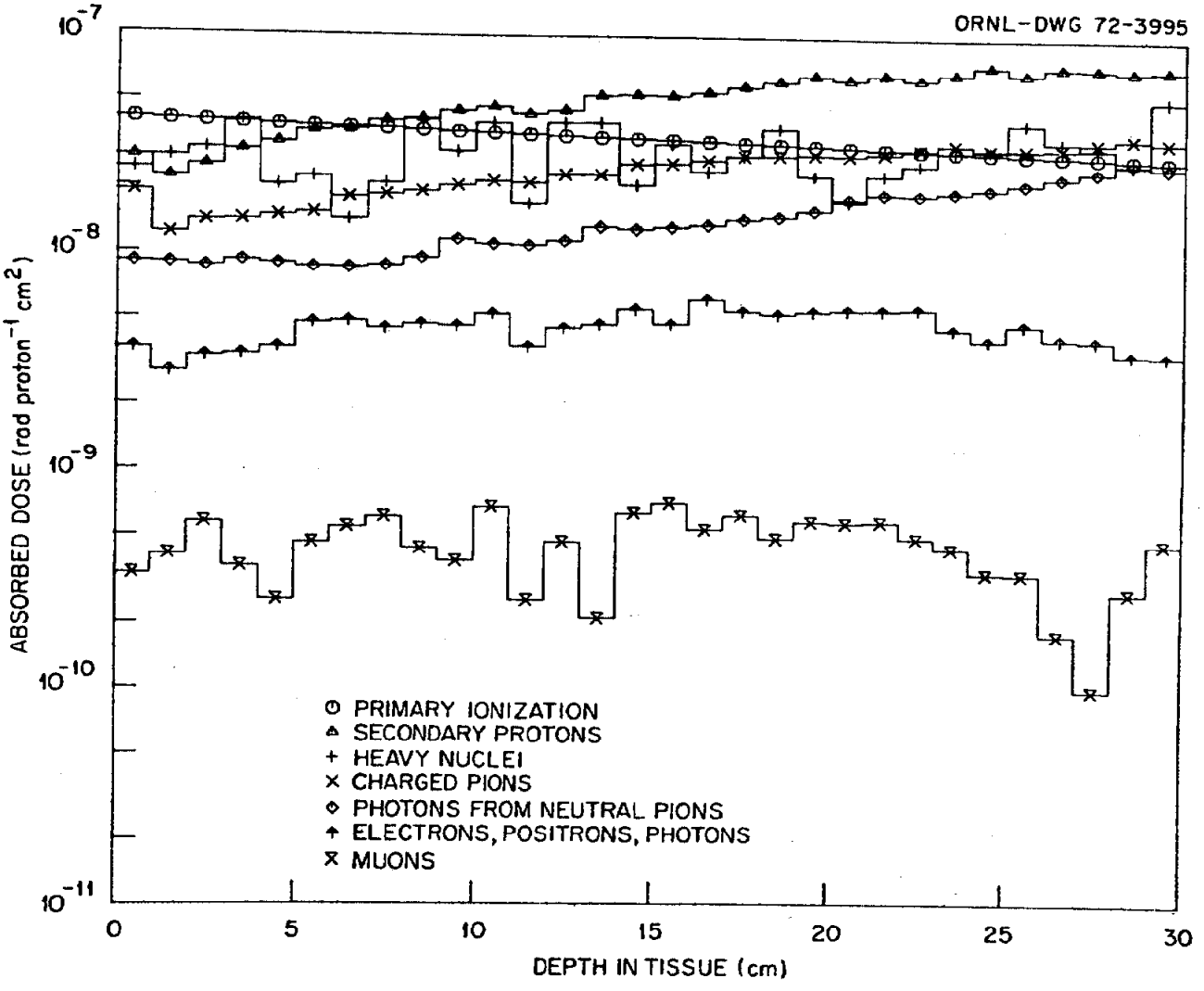

Fig. 3. Contributions to the absorbed dose for 100-GeV normally incident protons.

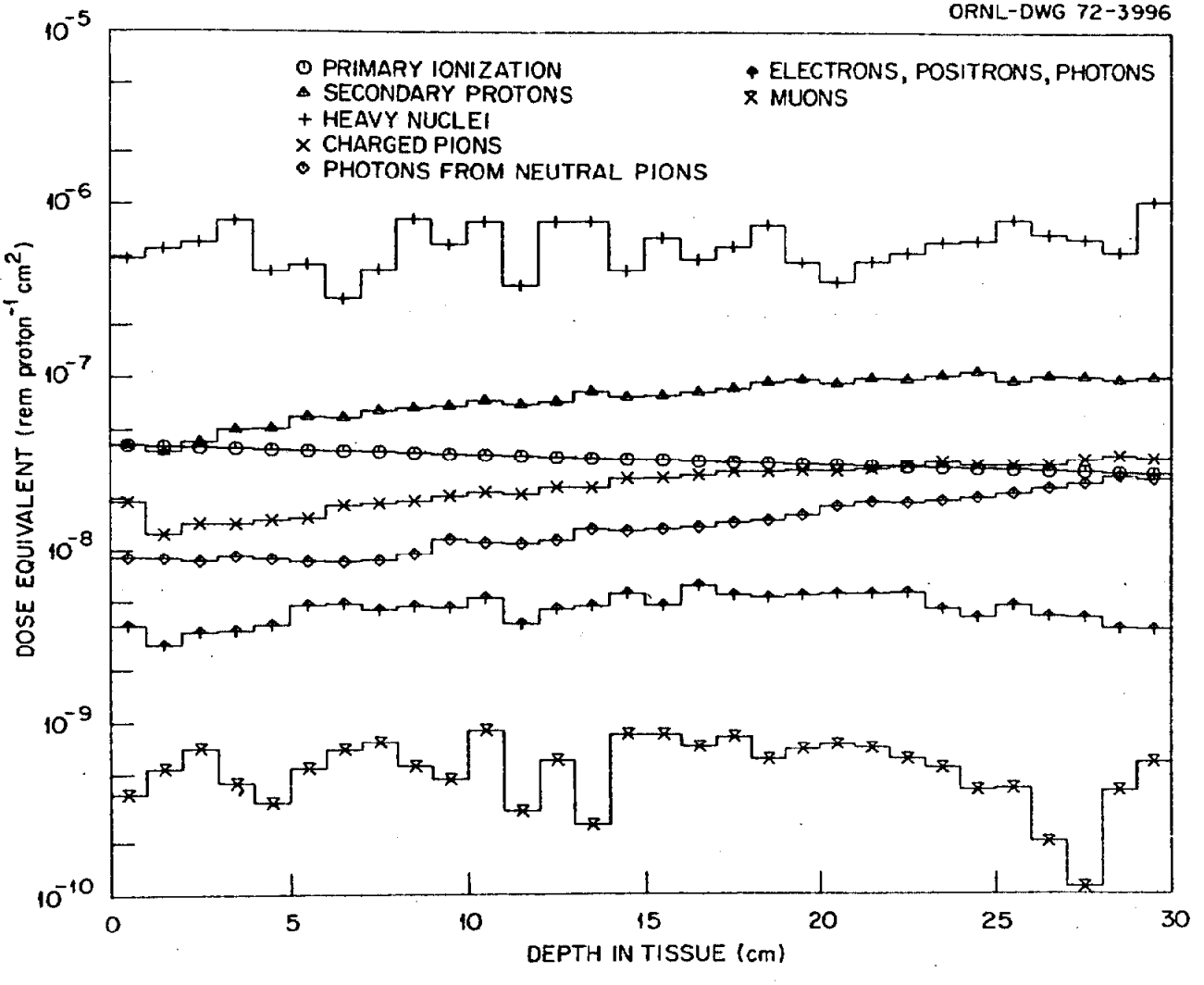

Fig. 4. Contributions to the dose equivalent for 100-GeV normally incident protons.

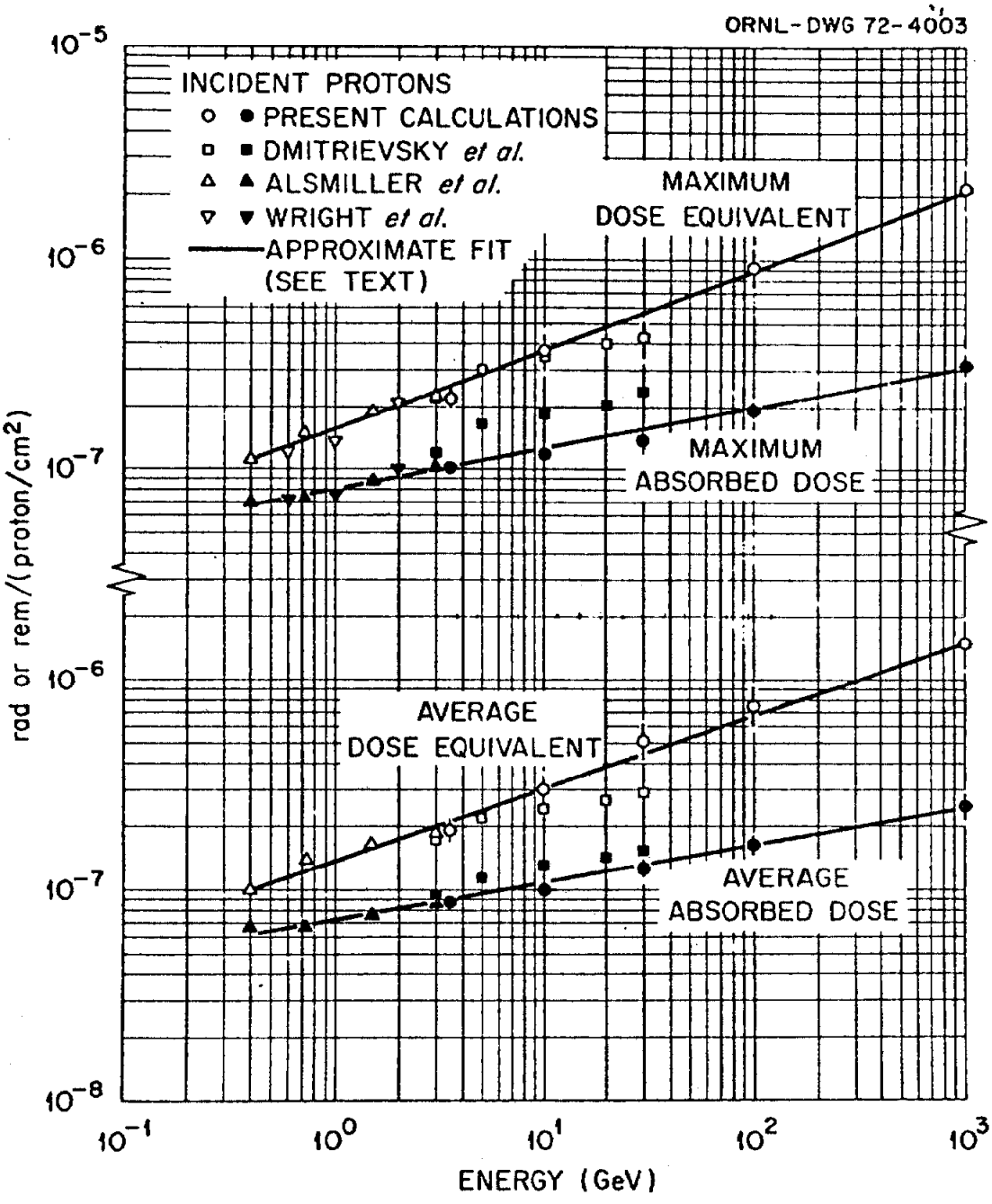

Fig. 11. Maximum and average absorbed dose and dose equivalent for normally incident protons. In addition to the present results, the results of Dmitrievsky *et al.*,[24] Alsmiller *et al.*,[1] and Wright *et al.*[2] are also shown.

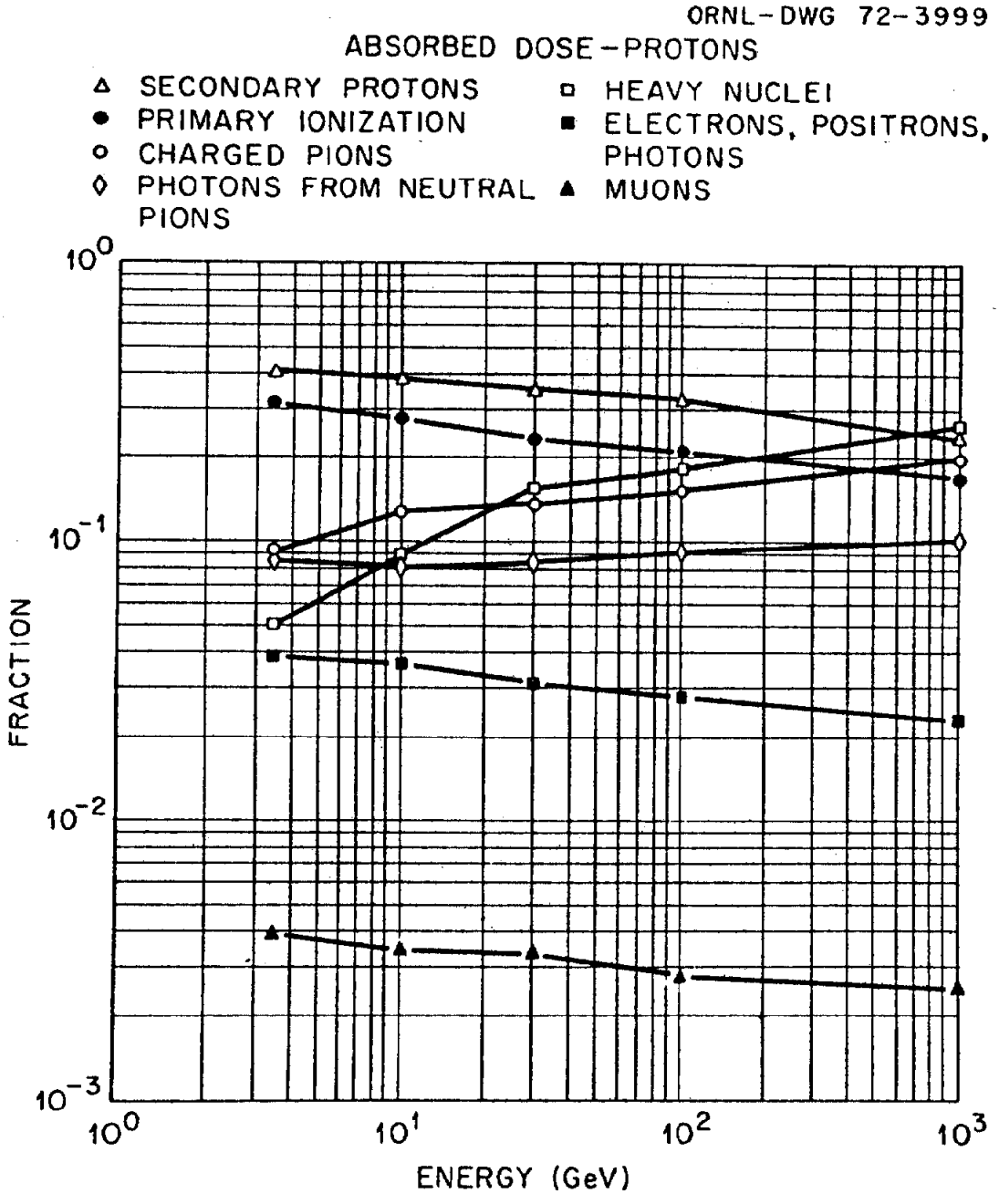

Fig. 7. Fractional contribution by various kinds of particles to the average absorbed dose produced by normally incident protons at various energies.

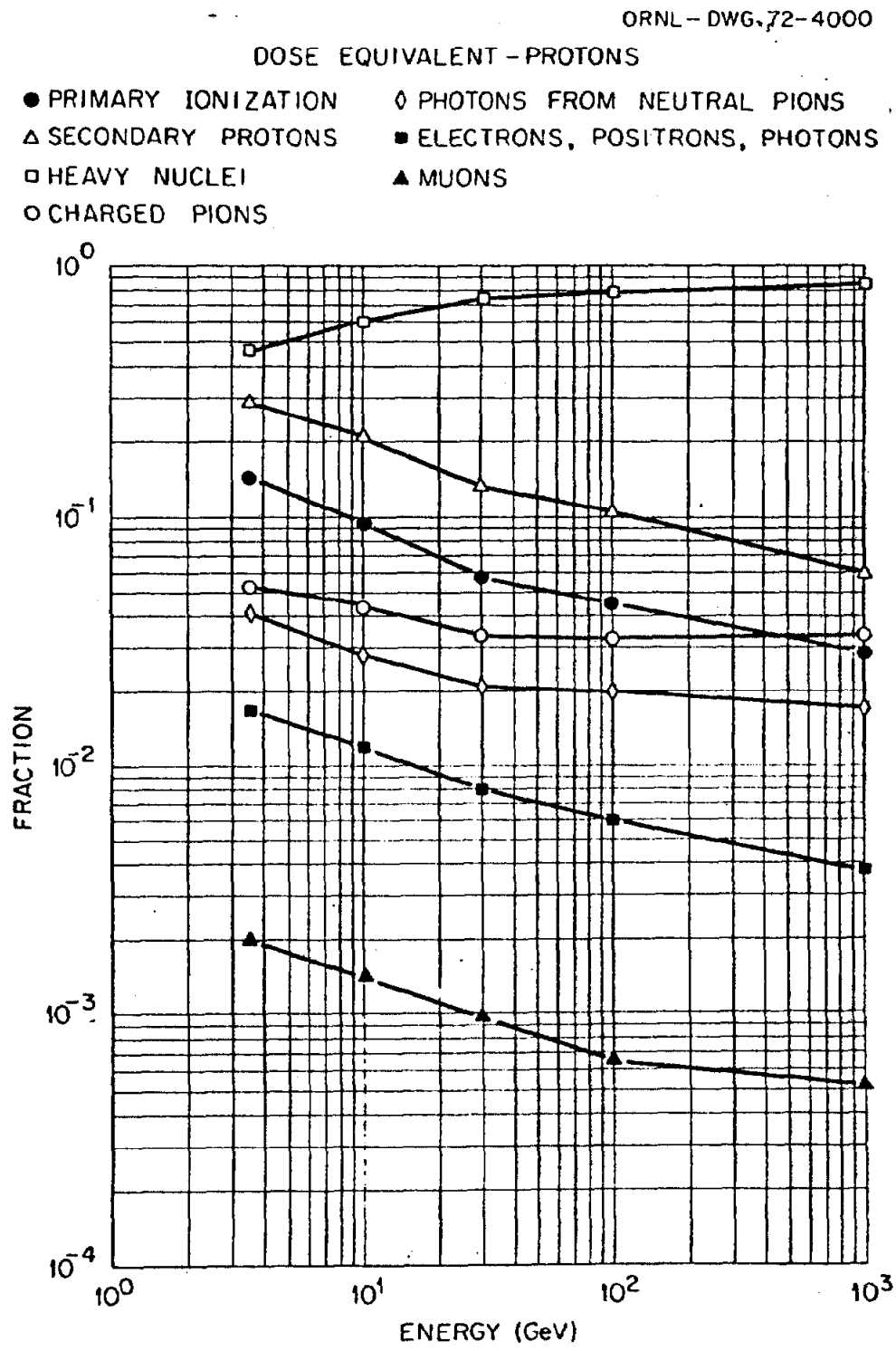

Fig. 8. Fractional contribution by various kinds of particles to the average dose equivalent produced by normally incident protons at various energies.

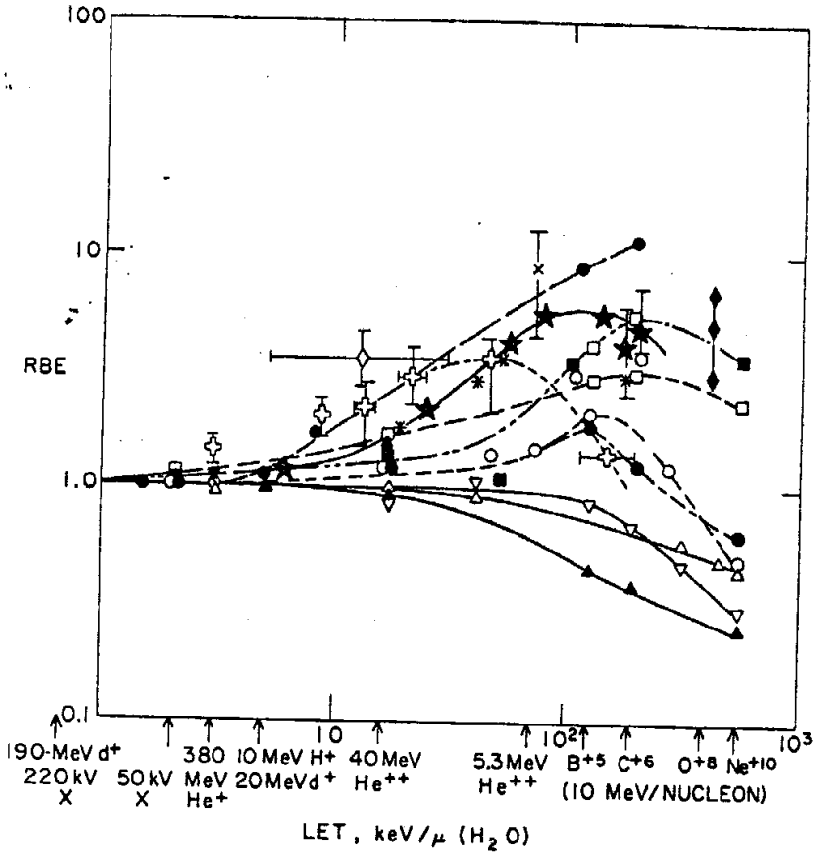

*Fig. 2.1. Experimental curves of RBE versus LET. ▲, T1 bacteriophage in broth. ▽, Shigella sonnei in O_2 (in N_2, behaves like type 2). △, Trypsin, lysozyme, DNase, dry, --●. Haploid yeast survival in air, induced reversions in diploid S. cerevisiae, survival. □, Diploid yeast survival in air. ■, Haploid or diploid S. cerevisiae in N_2. ♦, Artemia eggs, hatching or emergence. ★, Mammalian tissues, various. *, Mammalian tissues, various. X, Broad bean root, various effects on growth and survival. Tradescantia microspores, chromatid and isochromatid breaks. Rabbit crystalline lens cells, destruction and division effects, mammalian injury up to LET 20. ●, Stichococcus, survival. (From BNL - 50073.)*

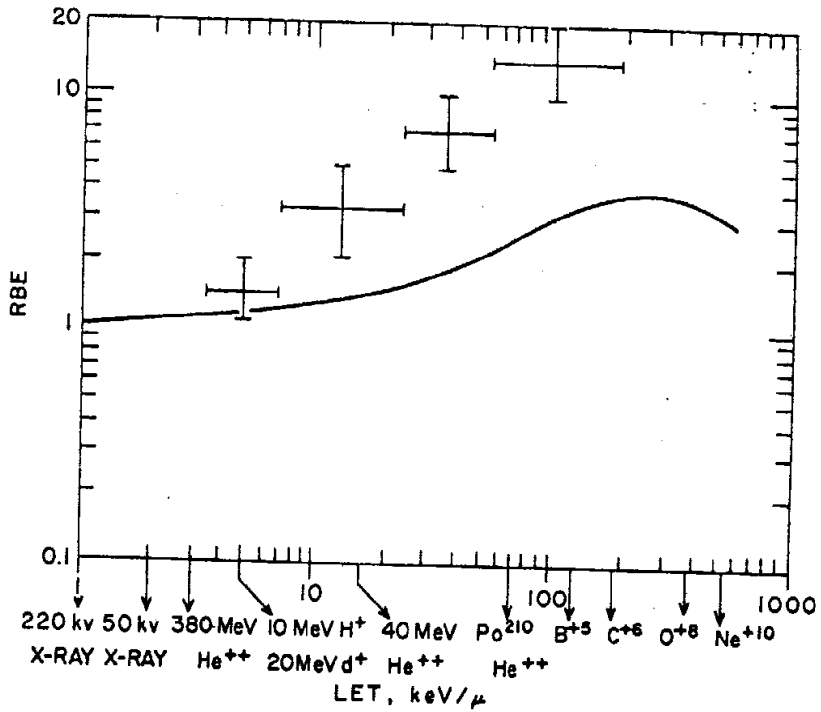

Fig. 2.2. Schematic curve summarizing the response of mamalian cells shown in Fig. 2.1. The crosses identify current values of Quality Factors recommended by ICRP. (After BNL - 50073.)